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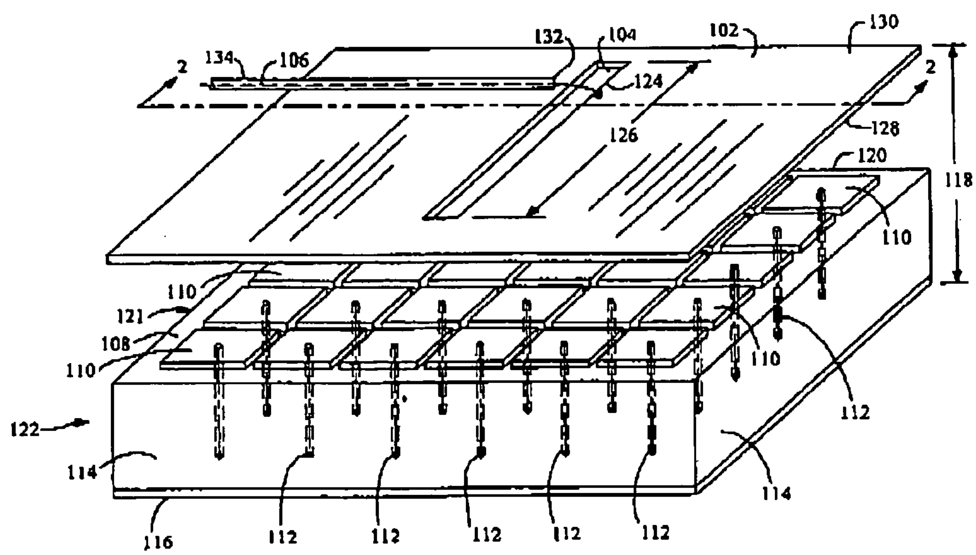

(57) Abstract: An antenna (100) comprises a conductive member (102) having an opening (104) for radiating an electromagnetic signal. A circuit board (122) is spaced apart from the conductive member (102) by less than one-quarter wavelength of the electromagnetic signal. The circuit board (122) has a series of conductive cells (110) for suppressing at least one propagation mode propagating between the conductive member (102) and circuit board (122) over a frequency bandwidth range defined by a geometric arrangement of the conductive cells (110).

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APERTURE ANTENNA HAVING A HIGH-IMPEDANCE BACKING

FIELD OF INVENTION

This invention relates to an aperture antenna backed by a high-impedance backing or a magnetic-field suppressive ground plane.

BACKGROUND

Antennas are used in a prodigious assortment of wireless communication applications. For example, portable wireless communications devices may use a straight conductor or an inductively loaded conductor as an antenna that extends from a housing of the communications device. The conductor may form a whip antenna which is subject to breakage from abusive treatment, or even ordinary wear and tear of wireless users. If the whip antenna is broken, bent or otherwise damaged, communications can be disrupted or become less reliable than would otherwise be possible. Further, the size of the protruding whip antenna may increase the overall size of the mobile wireless communications device.

To prevent damage to whip antennas and other external antennas that protrude from the housing of the wireless communications device, some manufacturers have introduced internal antennas that are housed within a housing of a mobile communications device. For example, an antenna may be fabricated as a cavity-backed aperture antenna within the housing of a wireless communications device. However, the nominal depth of the cavity-backed aperture antenna is approximately one-quarter wavelength of the frequency of operation. If the depth of the cavity-backed aperture antenna

could be reduced from the nominal value of approximately one-quarter wavelength, the size of the mobile communications device could be reduced accordingly, or additional electronics and functionality could be introduced in the same size of an electronic device. Thus, a need exists for an integral aperture antenna that has a thickness of or depth of less than one-quarter wavelength at the desired frequency of operation.

Another problem with the cavity-backed aperture antenna or other integrated antennas is that the surrounding electronics in the mobile communications device, or even the hand of a user of the communications device, can detune the antenna and degrade the radiation efficiency of the antenna. The surrounding electronics or body of the user may distort the antenna pattern from theoretically predicted results so as to produce unreliable communications that differ from what would be expected under ideal circumstances. Thus, a need exists for an antenna that reduces the effect of surrounding electrical components and the bodies of users upon the performance of an antenna integrated into a mobile communications device.

Although aperture antennas may be used for mobile communications devices, aperture antennas may be employed in a variety of environments such as antennas for vehicles, base station antennas, tower-mounted antennas for wireless infrastructure, or the like. If a whip antenna or half dipole antenna is mounted on an exterior of a vehicle it may impair the aerodynamic performance of the vehicle by increasing aerodynamic drag and reducing fuel mileage. Further, a protruding antenna on a vehicle is subject to damage or breakage from wind gusts, vandalism, and car washes. Thus, a

need exists for embedded, flush-mounted or other compact antennas for integration into a vehicle.

If aperture antennas or cavity-backed aperture antennas are used for wireless infrastructure applications, the antennas may be larger than desired for reduction of wind-loading, ease of installation and enhancement of aesthetic appearance. Space limitations on cramped towers or other structures tend to increase the desirability for smallest profile antennas with comparable performance to larger antennas. Thus, a general need exists to provide a compact antenna that provides adequate radiation performance while achieving aesthetic or space-saving goals.

SUMMARY

In accordance with one aspect of the invention, an aperture antenna comprises a conductive member having an aperture for radiating an electromagnetic signal. A high-impedance backing is spaced apart from the conductive member by less than one-quarter wavelength of the electromagnetic signal. The conductive member has a first surface area. The high-impedance backing has a second surface area that is commensurate in size to the first surface area. The high-impedance backing may comprise a pattern of conductive cells with intervening dielectric regions arranged to suppress at least one propagation mode in an open or closed cavity formed between the conductive member and the high-impedance backing over a frequency.

In accordance with another aspect of the invention, the aperture antenna may be readily fabricated as a circuit board assembly. Accordingly,

the conductive member may represent at least one metallic layer of a printed circuit board assembly. The high-impedance backing comprises a dielectric layer sandwiched between a pattern of conductive cells and a conductive layer. Further, the high-impedance backing includes at least some connective conductors (e.g., vias or plated through-holes) that electrically connect one or more of the conductive cells to the conductive layer.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of one embodiment of an antenna in accordance with the invention.

FIG. 2 is a cross-sectional side view of the antenna as viewed along reference line 2-2 of FIG. 1.

FIG. 3 is a perspective view of another embodiment of the antenna that features a solid dielectric layer.

FIG. 4 is a cross-sectional view of the antenna as viewed along reference line 4-4 of FIG. 3.

FIG. 5 is a perspective view of yet another embodiment of the antenna in which an opening has a diagonal orientation of its longitudinal axis with respect to a principal axis of a lattice of the cells of a high-impedance backing.

FIG. 6 is a perspective view of another embodiment of the antenna that includes a solid dielectric layer.

FIG. 7- FIG. 12 show various aperture shapes or geometric configurations of the conductive member for increasing bandwidth of the antenna in accordance with the invention.

FIG. 13- FIG. 18 show various bandwidth-increasing openings incorporated into illustrative antennas in accordance with the invention.

FIG. 19 is a perspective view of another embodiment of an antenna which features metallic side walls to form a generally closed cavity.

FIG. 20 is a cross-sectional view of the antenna as viewed from reference line 20-20 of FIG. 19.

FIG. 21 is a cross-sectional view of another embodiment of an antenna in which metallic side walls are formed by a linear series of plated through-holes.

FIG. 22 is a plot of an electric field propagated about a cross-sectional view of an aperture antenna in accordance with a prior art configuration.

FIG. 23 is a plot of an electric field propagated about a cross-sectional view of an aperture antenna in accordance with the invention.

FIG. 24 shows dispersion curves for the prior art antenna configuration of FIG. 22.

FIG. 25 shows dispersion curves for the antenna configuration of FIG. 23 in accordance with the invention.

FIG. 26 is a return lost diagram associated with the antenna of FIG. 5.

In FIG. 1 through FIG. 26, like reference numbers in different figures indicate like elements.

DETAILED DESCRIPTION

In accordance with the invention, FIG. 1 and FIG. 2 show an antenna 100. The antenna 100 comprises a conductive member 102 that has an aperture 104 or opening for radiating an electromagnetic signal, receiving an

electromagnetic signal, or for both radiating and receiving an electromagnetic signal. A transmission line 106 is coupled to an edge 124 of the aperture 104 for feeding the aperture 104 with an electromagnetic signal. A ground plane 116 of a high-impedance backing 122 is spaced apart from the conductive member 102 by a thickness 118 of less than one-quarter wavelength of the electromagnetic signal.

The high-impedance backing 122 may comprise a high impedance surface, such as a magnetic-field suppressive ground plane. A magnetic-field suppressive ground plane refers to a multi-layered structure in which the tangential magnetic field at a facing surface 121 or an exterior surface of the layers is suppressed over a certain range of frequencies. In general, a high-impedance backing 122 may be defined as a structure (e.g., a circuit board or a frequency selective high-impedance surface) where the ratio of tangential electric field to tangential magnetic field at a facing surface 121 of the structure exceeds some minimum ratio or approaches infinity. That is, a high impedance of the high-impedance backing 122 refers to a complex surface impedance that has a complex magnitude which exceeds the intrinsic wave impedance of a plane wave traveling in the medium (e.g., a dielectric medium or air) adjacent to and bounded by the surface. The complex surface impedance refers the ratio of total tangential electric field to total tangential magnetic field at the surface. For a typical case of a high-impedance surface in free space, the intrinsic wave impedance represents the intrinsic impedance of free space, which is 120π or 377 ohms. For the more general case of a high impedance surface bounded by an isotropic dielectric medium

of relative permittivity ε_r, the surface impedance is said to be a high impedance for frequencies were the complex magnitude exceeds the plane wave impedance for that medium of $120\Pi\sqrt{\varepsilon_r}$.

Practical high impedance surfaces are low-loss surfaces such that the magnitude of the reflection coefficient is near unity for all frequencies. However, the reflection phase sweeps through zero degrees at the center of the high-impedance band. Thus, an alternate way to define a high impedance surface is to say that it is a low-loss, or lossless, reactive surface whose reflection phase varies between +90 degrees and -90 degrees over its high impedance bandwidth.

For certain high impedance surfaces, which may be referred to as Sievenpiper artifical magnetic conductors, the +/- 90 degree reflection phase bandwidth (B_R) of the high-impedance surface can be modeled in accordance with the equation:

$$B_R = \frac{f_0}{Z_0}\sqrt{L/C}$$

where

$$f_0 = 1/(2\Pi\sqrt{LC})$$

Is the resonant frequency, or the frequency where a zero degree reflection phase occurs, Z_o is the intrinsic impedance of the dielectric medium bounded by the surface, L is the effective inductance of the surface, and C is the effective capacitance of the surface. In foregoing equation, Z_o appears in the denominator. So, as the intrinsic impedance of the dielectric is decreased by dielectric loading, the bandwidth of the certain high impedance surfaces

actually increases. It is important to appreciate that the bandwidth of a high impedance surface is defined not only by its surface properties, but also by the properties of the medium exterior to or adjoining its surface.

The conductive member 102 may comprise a metallic sheet, a generally planar substrate having a conductive coating, a planar substrate having a conductive layer or film, or a portion of a printed circuit board assembly. Although the conductive member 102 may have a variety of geometric configurations in FIG. 1, the conductive member 102 is substantially rectangular and is commensurate in size with that of the high-impedance backing 122. For example, the conductive member 102 has a first surface area that is commensurate with or generally equal to a second surface area of the high-impedance backing 122. The first surface area is bounded by a first perimeter (e.g., a first rectangular perimeter) and the second surface area is bounded by a second perimeter (e.g., a second rectangular perimeter). The first surface area excludes the open area associated with aperture 104 or another aperture configuration. The first surface area may be less than the second surface area by the aperture area of any aperture configuration disclosed herein and still be regarded as commensurate with or substantially equal to the second surface area.

In one embodiment, the conductive member 102 comprises a generally continuous conductive surface, except for the aperture 104. The conductive member 102 may be conductive on an interior side 128, which faces the high-impedance backing 122, and an exterior side 130, which faces opposite the high-impedance backing 122. Alternately, the conductive member 102 may

be conductive on both the interior side 128 and the exterior side 130. For example, if the conductive member 102 refers to a metal or metallic sheet, the conductive member 102 may be conductive on both sides; whereas if the conductive member 102 is formed of a dielectric substrate with a metallic coating or metallic layer, the conductive member 102 may be conductive only on one side.

The aperture 104 in the conductive member 102 may refer to a generally rectangular slot, although other suitable openings of other geometric shapes and configurations may be used to practice the invention. Examples of other apertures or bandwidth-enhancing openings for enhancing the bandwidth over a generally rectangular slot are described subsequently herein. A length 126 of the aperture 104 may be based upon the wavelength or frequency of the electromagnetic signal that is intended to feed the antenna 100.

The transmission line 106 feeds the aperture 104 in the conductive member 102 at the edge 124 of the conductive member 102 with a connecting end 132 (e.g., a center conductor of a coaxial cable) so as to provide a desired impedance at an opposite end 134 of the transmission line 106. The impedance at the opposite end 134 of the transmission line 106 may be varied by connecting the connecting end 132 of the transmission line 106 to various points along the longitudinal edge 124 of the aperture 104. Although the transmission line 106 is shown as a coaxial cable in FIG. 1, the transmission line 106 may be formed of a microstrip transmission line, a strip-line transmission line, a coplanar waveguide, or any other type of

transmission line. Further, the transmission line 106 may be located on or may adjoin an interior side 128 of the conductive member 102 even though the transmission line 106 is shown overlying the exterior side 130 of the conductive member 102 in FIG. 1.

The high-impedance backing 122 is spaced apart from the conductive member 102 and a dielectric region 120 intervenes between the high-impedance backing 122 and the conductive member 102. As shown in FIG. 1, the dielectric region 120 may be an air gap, a vacuum, or an inert gas-filled region. Further, one or more dielectric spacers (e.g., columnar or cylindrical members) may be inserted in the dielectric region 120 to maintain a uniform spacing between the conductive surface 102 and the high-impedance backing 122. Dielectric spacers may not be necessary where the conductive member 102 and the high-impedance backing 122 are mounted to a common housing or supported by adhesives or mechanical fasteners for maintaining a reliable and uniform spacing between the conductive member 102 and the high-impedance backing 122.

In general, the high-impedance backing 122 has a series of conductive cells 110 arranged in a geometric pattern for suppressing at least one propagation mode from propagating between the conductive member 102 and the high-impedance backing 122 over a certain frequency range. The conductive cells 110 may comprise conductive patches, metallic patches, rectangular patches, loops, rectangular patches with cutouts, or other suitable metallic structures that in the aggregate are tuned to form a bandgap for at least one propagation mode. The geometric pattern may represent a periodic

array of conductive cells 110, a lattice of cells 110, or some other arrangement of cells 110 in one or more layers. The conductive cells 110 are separated from one another by insulating regions 108 of the high-impedance backing 122.

The conductive cells 110 need not be generally rectangular as shown in FIG.1. In other embodiments, the cells 110 may be generally triangular, hexagonal, polygonal, annular, looped; or the cells may have other geometric shapes. If the high-impedance backing has multiple layers of conductive cells 110, the different layers may have similar or dissimilar shapes and may be separated by an intervening dielectric layer. For example, the conductive cells 110 may take on the form of loops as taught in pending U.S. patent application serial numbers 09/678,128 and 09/704,510, entitled MULTI-RESONANT, HIGH-IMPEDANCE ELECTROMAGNETIC SURFACE (filed on October 4, 2000) and MULTI-RESONANT, HIGH-IMPEDANCE SURFACES CONTAINING LOADED-LOOP FREQUENCY SELECTIVE SURFACES (filed on November 1, 2000), respectively, which are incorporated herein by reference.

In one embodiment, the high-impedance backing 122 has a series of conductive cells 110, which may be arranged as islands or otherwise. Although the conductive cells 110 of FIG. 1 are generally separated from one another by a dielectric pattern or insulating region 108 of the high-impedance backing 122, in an alternate embodiment the conductive cells 110 may be electrically connected by bridges of conductive material to provide desired broader bandwidth characteristics of the high-impedance backing 122.

At least some of the conductive cells 110 are connected to a conductive ground plane 116 of the high-impedance backing 122 by one or more connective conductors 112, plated through-holes, or other vertical conductors. In one embodiment, all of the conductive cells 110 are connected to the conductive ground plane 116. For example, in FIG. 1 and FIG. 2, each conductive patch 110 is connected to the ground plane 116 through its connective conductor 112 (e.g., a via or a plated through-hole). In another embodiment, some subset of the conductive cells 110 may remain isolated and may not be in direct current (DC) electrical contact with the ground plane 116. The connective conductors 112 are surrounded by a dielectric filler 114.

In an alternate embodiment, the dielectric filler 114 may be an air dielectric.

In one embodiment, the high-impedance backing 122 may be referred to as one or more of the following: an artificial-magnetic conductor ground plane, a frequency-selective high impedance surface, a high-impedance ground plane, and a magnetic-field suppressive ground plane. The series of cells 110 and the insulating region 108 or insulating pattern on the interior surface are arranged so as to inhibit the tangential magnetic field from propagating on an exterior surface of the high-impedance backing 122 adjacent to the dielectric region 120. The height of dielectric region 114 may also be selected to inhibit the tangential magnetic field from propagating in a region between the high-impedance backing 122 and the conductive member 102.

An artificial magnetic conductor refers to a structure where the magnitude of the tangential magnetic field approaches zero over a limited range of frequencies, whereas in a perfect electric conductor the magnitude of the tangential electric field approaches or equals zero as a boundary condition. In practice, the arrangement of conductive cells 110 provides such a high impedance (at the facing surface 121) to the tangential magnetic field over a limited bandwidth about a backing resonant frequency range so as to inhibit the tangential magnetic field from supporting propagation pursuant to various parasitic or unwanted propagation modes.

The aperture 104 may be characterized by an aperture resonant frequency range that is determined at least partially by the dimensions and the shape of the aperture 104. A maximum aperture length 126 refers to one dimension of the aperture 104. The aperture resonant frequency range and the backing resonant frequency range are ideally aligned or overlapped to a sufficient extent to produce an overall resonant frequency response at a desired antenna frequency or over a desired an antenna frequency range.

A facing surface 121 (formed by the combination of cells 110 and an insulating region 108) of the high-impedance backing 122 may be configured consistent with an assortment of geometric configurations that provide a high impedance to at least one unwanted propagation mode over a certain bandwidth. One or more of the following propagation modes may be inhibited from propagating in the dielectric region 120 or in another region between the conductive member 102 and the ground plane 116: a transverse electric (TE) mode, a transverse magnetic (TM) mode, a transverse electromagnetic (TEM)

mode, a longitudinal section electric (LSE) mode, and longitudinal section magnetic (LSM) mode. LSE and LSM modes are variations of TE and TM modes, respectively.

The foregoing TE, TM, and TEM modes may be referred to as lateral guided wave modes. The lateral guided wave modes may be excited in an antenna configuration that includes parallel plate conductors such as that generally formed by the conductive member 102 and the metallic ground plane spaced apart from the conductive member 102 by approximately one-quarter wavelength. Because the lateral guided wave modes or other parasitic modes excited by the aperture 104 are prevented or inhibited from propagating, the antenna 100 prevents the formation of unwanted side lobes or pattern distortion (e.g., ripple) in the radiation pattern of the antenna 100. The radiation pattern of the antenna 100 may provide a generally hemispherical radiation pattern, a generally unidirectional radiation pattern from the aperture 104, a substantially cardioid radiation pattern or some other pattern.

The inhibition of the propagation of the parasitic modes of propagation allows the antenna of the invention to be constructed in accordance with at various configurations. Under the configuration of FIG. 1 and FIG. 2, the lateral sides of the antenna 100 are not enclosed with any conductive side walls adjacent to or surrounding the dielectric region 120. The arrangement of the conductive cells 110 and facing surface 121 of the high-impedance backing 122 inhibits the propagation of parasitic electromagnetic modes over a certain bandwidth to compensate for or accommodate the absence of any

conductive side walls. Accordingly, in FIG. 1 the configuration of the antenna 100 reduces the manufacturing cost and reduces the manufacturing cycle-time or complexity of the antenna in accordance with the invention by eliminating the need to fabricate the antenna 100 without any lateral vertical conductive side walls for electromagnetic shielding.

In a preferred embodiment, the height or thickness 118 of the antenna 100 from the conductive member 102 to the conductive ground plane 116 is less than one-quarter wavelength at the resonant frequency of the aperture 104 or the antenna 100. Accordingly, the antenna may be readily integrated into a portable wireless communications device where compact designs are desirable. Further, the antenna may be integrated into a conformal antenna or embedded antenna designs for vehicles where space conservation and reliability are concerns.

In one configuration, the height or thickness 118 may range from approximately one-twenty-fifth of the wavelength at the frequency of operation to one fiftieth of the wavelength at the frequency of operation to further enhance the space efficiency of the antenna of the invention.

The radiation pattern from the aperture antenna 100 with the high-impedance backing 122 provides a unidirectional pattern such as a hemispherical pattern. Further, the predicted radiation pattern may remain intact even if the antenna is mounted directly on another metal surface or placed in proximity to another object (or person) because of the electrical isolation achieved by the high-impedance backing 122 configuration having the arrangement of conductive cells 110.

The configuration of the antenna 100 of FIG. 1 allows the lateral sides to be open or not shielded without producing a serious electromagnetic interference to other nearby system components of electronic devices such as portable wireless communications devices.

In accordance with one aspect of the invention, the aperture antenna (e.g., antenna 100) of the invention may be readily fabricated as a circuit board assembly. Accordingly, the conductive member 102 may represent at least one metallic layer of a printed circuit board assembly. The high-impedance backing 122 comprises a dielectric layer sandwiched between a pattern of conductive cells 110 and a conductive layer (e.g., conductive ground plane 116). Further, the high-impedance backing includes at least some connective conductors 112 (e.g., vias or plated through-holes) that electrically connect one or more of the conductive cells 110 to the conductive layer.

The high-impedance surface 122 suppresses at least one propagation mode from propagating between the conductive member 102 and pattern of conductive cells 110 over a frequency bandwidth range defined by at least the arrangement of the conductive cells 110, connective conductors 112 (e.g., vias), and a dielectric properties of the high-impedance backing 122. The connective conductors 112, the conductive cells 110, dielectric spacers, and other features of the antenna are readily produced by circuit-board processing techniques or other low cost manufacturing techniques described in pending U.S. application serial number 09/—,—, entitled ARTIFICIAL MAGNETIC CONDUCTOR SYSTEM AND METHOD OF MANUFACTURING, filed on

April 27, 2001, and invented by James D. Lilly, which is incorporated herein by reference. The above application entitled ARTIFICIAL MAGNETIC CONDUCTOR SYSTEM AND METHOD OF MANUFACTURING claims the benefit of provisional application serial number 60/271,235 (filed February 26, 2001), which is incorporated herein by reference.

In an alternate embodiment, the transmission line 106 of FIG. 1 and FIG. 2 is mounted within the interior cavity formed by the conductive member 102 and the high-impedance backing 122, as opposed to on or near an exterior side 130 of the conductive member 102. Advantageously, the transmission line 106 orientation on or adjacent to the interior side 128 permits the antenna to be configured in a substantially rectangular or polyhedral form for mounting in association with an electronic device or a wireless communications device.

FIG. 3 and FIG. 4 show another embodiment of the antenna in which the dielectric region 120 is filled with a dielectric layer 202. The antenna of FIG. 3 and FIG. 4 is designated by reference number 200. Like reference numbers in FIG. 1 through FIG. 4 indicate like elements.

The dielectric layer 202 may refer to a dielectric foam, a low density foam, a ceramic insulator, a polymeric insulator, a plastic insulator, honeycomb insulation, or another dielectric suitable for the frequency of operation. For example, if the dielectric layer is constructed of closed cell foam or another low-loss dielectric of sufficient thickness, the bandwidth of the structure may be enhanced over the use of a higher permittivity dielectric

region 120 between the conductive member 102 and the high-impedance backing 122.

The dielectric layer 202 may have a dielectric thickness 119 that is selected to provide the lowest possible thickness 118 (i.e., depth) of the antenna or the lowest possible depth that meets a minimum bandwidth criteria. Accordingly, the dielectric layer 202 may have a dielectric thickness 119 between approximately one fiftieth (1/50) of a wavelength and approximately one-tenth (1/10) of a wavelength at a frequency of operation of the antenna. For example, the dielectric layer 202 may have a dielectric thickness 119 of approximately one twenty-fifth (1/25) of a wavelength at the frequency of operation.

The dielectric layer 202 may have a dielectric thickness 119 that is selected to provide the greatest possible bandwidth for an overall profile of the antenna that is less than one-quarter (1/4) wavelength in depth at the frequency of operation.

In an alternate embodiment to FIG. 3 and FIG. 4, an antenna includes a transmission line 106 that is routed within the dielectric layer 202. The transmission line 106 would be disposed between the conductive member 102 and the high-impedance backing 122. Accordingly, the antenna would provide a polyhedral or a generally rectangular profile for mounting within or integrating it within an electronic device or another item.

FIG. 5 is another embodiment of an antenna. The antenna of FIG. 5 is designated by reference number 500. FIG. 5 is similar to FIG. 1 except for the orientation of the longitudinal axis of aperture 104 with respect to one

principal axis (504, 506) of the pattern of cells 110 on the high-impedance backing 122. Like reference numbers in FIG. 1 and FIG. 5 indicate like elements.

The aperture104 FIG. 5 has a longitudinal axis 502 that is parallel to or coincident with the greatest longitudinal length of the aperture 104. The maximum longitudinal length 126 of the aperture 104 is generally proportional to the frequency of operation of the antenna. A pattern may comprise a lattice of conductive cells 110. A lattice refers to a periodic or repetitive structure of cells 110 in a high-impedance backing 122. If the lattice is a two-dimensional lattice, each of the cells 110 may be bound by a first principal axis 504 and a second principal axis 506 that extend from a common vertex. The first principal axis 504 and the second principal axis 506 may be referred to collectively as principal axes. Although the principal axes are generally orthogonal to each other in FIG. 5, the principal axes may form other angles with respect to each other that depend upon the cell geometry of the high-impedance backing 122.

Here, as shown in FIG. 5 the cells 110 are generally rectangular and arranged in rows so as a to form a grid for the cell geometry. The principal axes (504, 506) are parallel to or coincident with the rectilinear dimensions of the grid. Accordingly, the longitudinal axis 502 of the aperture 104 forms an angle (θ) with one principal axis 504 of the high-impedance backing 122. As shown, the angle θ is approximately 45 degrees, although in an alternate embodiment the angle θ may range from zero to 90 degrees. At approximately 45 degrees or another suitable angle, the bandwidth of the

antenna may be enhanced. The preferential angle for angle θ may be determined empirically or an a trial-and-error basis, for example.

The enhanced bandwidth of the antenna may be defined by a return loss having a greater frequency range that exceeds a minimum return loss suitable for an impedance match to a transmitter or a receiver coupled to the antenna, for example. The bandwidth of the antenna 500 refers to not only the bandwidth of the aperture 104 or aperture bandwidth, but the aggregate overall bandwidth produced by the cooperation of the aperture bandwidth and the backing bandwidth of the high-impedance backing 122. An illustrative example of an improvement in bandwidth, as expressed in return loss bandwidth, is described later with reference to FIG. 17.

FIG. 6 is similar to FIG. 5 except FIG. 6 includes a solid dielectric layer 202 sandwiched between the conductive member 102 and the high-impedance backing 122. The antenna of FIG. 6 is designated by reference numeral 600. Like reference numbers in FIG. 5 and FIG. 6 indicate like elements.

The dielectric thickness 119 of the dielectric layer 202 may be greater than or equal to approximately one-tenth (1/10) of a wavelength to increase the bandwidth of the antenna 600 over that of a thinner dielectric layer, regardless of whether the antenna 600 has a diagonally oriented aperture 104 or not.

FIG. 7 through FIG. 12 show various configurations for bandwidth-enhancing apertures 700 in the conductive member 102. Like reference numbers indicate like elements in FIG. 7 through FIG. 12.

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